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ASSESSING IMPACTS OF MODULAR PRODUCT ARCHITECTURES ON THE FIRM: A CASE STUDY

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1. Introduction

During product development, engineers and managers define product properties, including functions, ergonomics, and production, and have to make decisions that have far-reaching consequences for their company. In practice, products are developed within product development projects. Consequences are triggered by the decisions made by development teams. As product development, from an overall perspective, creates sustainable and successful return on investment, there are also effects on the company and its success. Product development, in most companies, takes place in an existing portfolio, which is challenging because new requirements and boundaries resulting from the existing portfolio have to be considered. Powerful examples of ways to manage product portfolios and product architecture are modularization and platform approaches. However, product modularization is difficult and has far-reaching impacts for the company. It requires a sound understanding of cause and effect chains, which start with basic product structure decisions, such as module boundary definitions or interface specifications, and lead to essential target values consisting of cost, quality and time categories for each product and the product portfolio.

Complexity in decision making during development projects [Marques et al. 2010] is exacerbated when effects of decisions are not known, e.g. in the context of modularity and platforms. Knowledge of these effects represents a major competence for decision making in module definition and starts with basic engineering, business economics and management understanding. The modular structure of a product has broad impacts across company functions. Thus, necessary knowledge stretches to include company and product-specific effect chains across company functions. Decision making in product modularization requires sound and linked knowledge across many domains. To provide decision makers with necessary knowledge, coherences between properties and effects of modular product structures can be modeled by principles such as cause and effect chains.

This paper summarizes suitable effects and effect models for product architecture from the literature. Following an industry case study on a power tool company, challenges in assessing the impacts of modular product structures are identified and an impact model is derived. The results of the case study demonstrate the effects of decreasing and increasing modularity on a product development project and on a company. Conclusions on providing support for decision makers in the context of modular product definition are then derived.

2. Literature review

The power of product platforms and modularization effects has been widely investigated in past research. Increasing competition, customer demands and shorter product life cycles are triggers for systematic product architecture approaches, such as platform and modularization approaches. Methods for developing modular product structures have been postulated, such as Modular Function Deployment [Erixon 1998], Structural Complexity Management [Lindemann et al. 2009], Theory of Modular Design [Stone 1997] and Integration Analysis Methodology [Pimmler and Eppinger 1994], and methods for assessing product architectures, such as variance flexibility [Erixon 1998], evaluation metrics [Hölttä-Otto and Otto 2006], platform commonality index [Siddique and Rosen 1998] and the Degree of Commonality Index [Collier 1981].

Power of modular product structures

The power of product architecture approaches, such as platforms [Harland and Uddin 2014] and modular product structures, has been the focus of research in recent decades. Promising results have been found, and many companies utilize the approaches. [Harland and Uddin 2014] analyse 27 effects of product platforms in literature, such as covering multiple market segments, reducing production cost, reducing time to market, reducing product cost, increasing (external) variants and reducing development costs.

One effect of modular product structures is on complexity costs. [Ripperda and Krause 2014] point out the importance of cost estimation approaches and further identify seven clusters in current research. The determination of complexity costs in modular structures is difficult since they are not directly attributable to one product. A particular property of complexity costs is that they impact all life phases of a product and other product families. According to the findings of [Dahmus et al. 2001], lifecycle costs have a big impact on module definition and are therefore directly linked to architecture decisions.

Impact models of effects of product platforms and modular product families

Few models can be found in literature that describe the network of interdependencies of the properties of modular product structures and firm objectives. Individual effects are often described but an overall view is rarely given. [Harland and Uddin 2014] present a model that relates modularity to company success factors. They predominantly show direct and indirect effects, such as reduced time to market, which directly improves cost and competitive advantage. [Boer 2014] approaches the impact model from the product development perspective, defining characteristics of product modularity as being standardized modules and interfaces and specific functions. She builds a three stage model that is divided into effects on the product, operations and performance. Overall strategic firm aspects are not given.

Several statistical models based on structural equation modelling can be found in literature. They deal with effects of modularity on company success factors and statistically prove that product modularity positively affects flexibility and delivery, and therefore product performance [Lau et al. 2007], and that product modularity reduces the time required for new product development [Danese and Filippini 2013]. Since these models are developed mainly from the business economic perspective, they lack any relation to product development or product structure. To use the power of modular product architectures, the perspectives need to be connected to be able to predict impacts.

To support decision making and to assess modular product structures, metrics to measure the product structure and its performance have been developed. However, current metrics are characterized by a lack of applicability and are incomprehensible. The assessment of strategic and monetary effects fails in practical environments due to the lack of structured and formal information [Heilemann et al.2013].

3. Problem statement

The missing link between product architecture decisions and company objectives

Research in modular product development postulates the importance of having detailed knowledge about product architecture decisions and their impacts. This knowledge plays an important role in the definition of product architecture, which later contributes to product development projects and company success. The system of objectives to be optimized, measurements of performance, and the degrees of freedom in product architecture design are not sufficiently linked to provide support for decision makers. Success factors in companies are often measured by financial KPIs, such as Earned Value Added (EVA), Weighted Average Cost of Capital (WACC), Return On Capital Employed (ROCE) and turnover [Gries and Restrepo 2011], whereas product development teams have to make decisions within their project operation system and are typically measured by development lead-time or technical design targets. Engineers who actually design products and components determine, consciously or unconsciously, later properties and the product architecture, which includes module or platform definition. [Salvador 2007] offers five definitional perspectives, consisting of component commonality, component combinability, function binding, interface standardization and loose coupling. Project teams ideally make decisions and design their product architecture so that the decision optimizes the systems of objectives. To provide sufficient support when defining product structures, properties of product structures and modular structures have to be linked with the product strategic perspective, including effects on system of objectives (Figure 1).

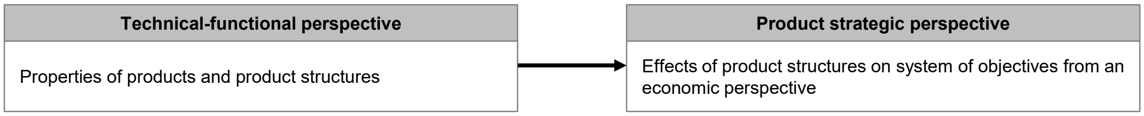

Figure 1. Needed connection between product related perspective and product strategic perspective

Supporting decision makers

There is a lack of knowledge on supporting decision makers in decisions related to product architecture, such as variant decisions, platform decisions and decisions in modular concept design [Ponn 2015]. However, the positive effects of variance reduction and platform approaches have been widely investigated. Negative aspects, especially trade-off effects within a decision situation and their impacts on the system of objectives, have not been investigated sufficiently to support decision makers. Trade-offs, e.g. for commonality, such as described in [Simpson et al. 2014], trigger the need for a detailed and differential view of cause and effect chains in product architectures. Building on this, there is a lack in research in investigating impacts of modular product structures and in supporting decision makers (e.g. engineers, project managers, steering boards, portfolio managers and upper management) in assessing the impacts on individual projects and companies.

This paper aims to analyse the impacts put forward by several researchers and to derive an impact model for a product architecture decision, based on an empirical case study. This case study highlights challenges in assessing the impacts of product architecture decisions (which is a decision of modularity in the case study) and derives an impact model. The effects are analysed and interlinked with the system of objectives. It is assumed that effects described in literature can be observed, since the structure of the products in the case study are similar, especially the ones described in [Harland and Uddin 2014], such as reduced design complexity, increased quality, increased profit, reduced development costs and coverage of global markets. Thus, this paper demonstrates the correlation between the decrease and increase in properties of modularization [Salvador 2007] and its effects.

4. Case study on an international power tool company

4.1 Research methodology

The case study described below is on the power tool company Hilti and was carried out in the product development department. The research focus was a development project for a power tool. During the study, data were collected for eleven months and included the researcher as an observer and participant. To ensure a detailed coverage of data, multiple data collection methods, such as observations during project meetings, analysis of project documents, observation of product steering meetings, interviews with relevant stakeholders of the project and interviews with the responsible project manager, were used. During the study, there was a strong focus on isolating the effects of the variant decision; other influencing factors and product architecture relevant factors were separated. The effect chain of the decision and its direct and indirect impacts on this internal variant decision could be isolated from other influences and analysed in detail.

Impacts, correlations and cause and effect chains were then defined as they were discussed during meetings or had significant influence on the project or firm, or were investigated by the project team but not relevant to the final decision. To ensure understanding and comparability of the effects described, terminology and definitions by specific authors were used: product architecture [Ulrich and Eppinger 2004], product structure [Pahl et al. 2007], platforms [Meyer and Lehnerd 1997], variants [Franke et al. 2002] and modular product families [Rupp 1980]. Table 1 summarizes the research methodology key characteristics, based on the characterization scheme of [Blessing and Chakrabarti 2009].

Table 1. Characteristics of case study

Dimensions	Characteristics
Purpose of the study	Identifying the impacts of internal variance on the firm
Nature of the study	Interventional
Theoretical basis	Impact model postulated by [Harland and Uddin 2014]; [Salvador 2007]; [Simpson et al. 2014]; Integrated PKT approach [Krause et al. 2014]
Units of analysis	• Product, properties of modularity, internal variance • System of objectives (e.g. cost metrics, lead time) • Correlations between properties of modularity [Salvador 2007] and project goals or company system of objectives
Data collection methods	Observation of project meetings, analysis of project documents, observation of project steering meetings, interviews with relevant stakeholders of project, interviews with project manager
Coding and analysis methods	Impacts, correlations and cause and effect chains were defined as they were discussed during meetings or had significant influence on the project or on the company or were investigated by the project team
Duration	Eleven months

4.2 Hilti corporation

The Hilti corporation provides products and services for professional construction applications. As well as offering solutions in consulting, anchor systems and fire protection, Hilti also has a strong focus on solutions for power tools. The power tool portfolio is structured in product lines, some examples of which are screw drivers, breakers, rotaries, combihammers and diamond systems.

Products are developed within a stage-gate process, a process consisting of six gates and five phases. Phase 1 includes activities such as defining the engineering task. In the second phase, design concepts are derived. Before the project passes the third gate, design concepts are validated. The focus of phase 4 is to verify the development results before the subsequent phase of preparation for serial production. After Gate 5, serial production of the tool starts. The process ends with gate 6, where the handover to product care takes place and the product development team responsibility for this project ends [Gasnakis 2011].

4.3 Development project

The chosen product family consists of two power tools. The development project of power tool A is ahead of power tool B. From an application perspective, and therefore also from a functional perspective, both tools are similar but differ in parameters, e.g. output power.

The case study was conducted before gate 3 of power tool B. The development team had to define the concept, which includes definition of the product structure and mechanic, electric, electromagnetic and software design of the product. For the project team, gate 3 is a major milestone since the overall engineering design is frozen here.

As [Gasnakis 2011] and [Ponn 2015] describe, the company uses a platform-driven approach for electronics, utilizing a matrix organization. The development team for power tool B consists of several domains, as described in [Gasnakis 2011]: project manager, technical project manager, mechanical engineering (e.g. chuck, hammering mechanism and gear), drive and electrical engineers (e.g. software engineers, electrical engineers) and supply managers.

According to [Kreimeyer 2014] and [Ponn 2015], visual approaches, such as the Integrated PKT approach [Krause et al. 2014], are crucial for managing internal and external product families as they create transparency, not only in the product portfolio but also in the product structure of the product family. The product structure of the chosen product family is illustrated in Figure 2 using the approach of [Krause et al. 2014]. The methodology, Modular Interface Graph (MIG) [Krause et al. 2014], visualizes the design concept, rough layout of each module and the final product structure. The product has a distinctly modular character and is broken down further into modules, as illustrated in Figure 2 via a Modular Interface Graph (MIG) [Krause et al. 2014].

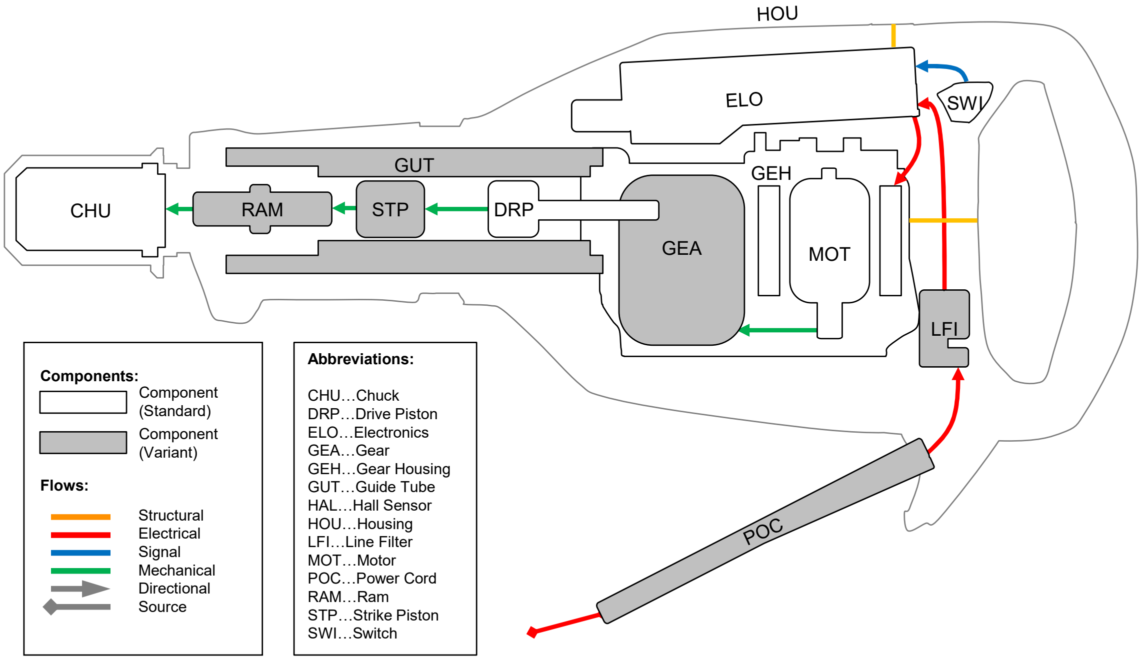

Figure 2. Modular Interface Graph (MIG) of power tool A and B

4.4 Variant decision point during the development project

Product development is dynamic in its changing requirements and boundaries. During the development project, the team for power tool B had the option of adopting the design of the electronics developed by power tool project A and to meet upcoming, but undifferentiated requirements, and create internal variance in the product family of power tools A and B. The alternative was to implement existing electronics and to keep internal variance low. During the development process, product architecture alternative 2 was discussed and assessed.

Power tool A and power tool B could both use a modular approach in the electronics module, due to their similarities at functional and application levels. However, since the effects of the alternatives were not fully transparent from the very beginning, the project team of power tool B investigated the impact of developing new internal variance for the electronics.

The team of power tool B therefore had two fundamental degrees of freedom from a product architecture perspective (Figure 3):

1. Alternative 1: Implement the same electronics developed to serial production maturity in both tools, according to the stage-gate process described in Section 4.2. Alternative 1 represents the modular approach by using the same electronics module, which creates commonality.
2. Alternative 2: Adopt a single solution derived from the developed electronics in power tool A. This alternative can be characterized as a platform approach since there is commonality of components, manufacturing and engineering to a certain degree, as well as unique parts, which increase internal variance.

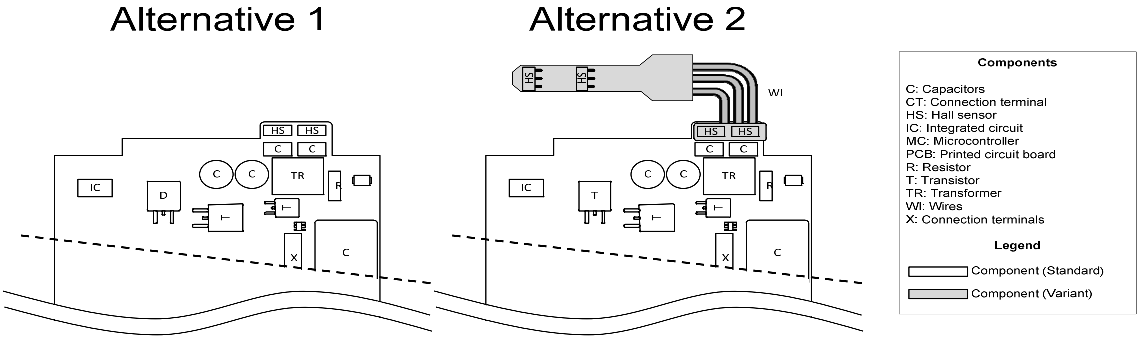

Figure 3. MIG of electronics module design alternatives

Both design alternatives and their variant parts are illustrated in Figure 3 in a MIG for the electronics module. The methodology highlights variant parts in product architecture alternative 2, and the reduced internal variance for product architecture alternative 1. The main differences in the design are highlighted in Figure 3 in grey (wires and hall sensors).

During project meetings, the impact of adaption and internal variance were discussed. Other impacted areas were also identified but had no significant impact on the decision since the impact was minimal compared to other impacts. The major decision challenges for the project team during the study were:

- Identify effects of the design alternatives: What are the consequences of choosing alternative 1 or 2?
- Assess effects of the design alternatives: How big is the influence on each objective?
- Handle multiple systems of objectives and assess trade-offs: How do we assess conflicts of objectives, e.g. conflicts in projects, departments and company objectives? How can opportunity costs be assessed?
- Foresee long-term and cross-portfolio consequences of product architecture decisions: How can suitable product architectures for our product families be defined? What modular strategy must be followed if certain effects are desired?

The electronics module and the choice thereof are determinative in achieving the project objectives. The challenges above were derived from the collected data and further consolidated.

4.5 Impacts of the variant decision on the project and company

During the development project, the team discussed the advantages and disadvantages of having one electronics system for both power tools or a solution for each. The impact of increased internal variance if alternative 2 was chosen is described below and summarized in an impact model. The reference scenario for the impact model is alternative 1.

Impact on lead time

Choosing alternative 2 has a significant impact on product development time and time to market, assuming the same resource availability per alternative. The baseline is alternative 1, which enables the shortest lead time. Besides causing additional variance in the firm, adapting the existing module creates engineering tasks. Effects on process commonality are significantly noticeable in software development, electrical and mechanical engineering, and approvals. The impact of this correlation is crucial to the development project and in the later decision. Average lead time increases by around 10% - 20%. The impact on lead time is mainly the result of decreasing commonality and increasing project risks. Lead time impacts turnover directly, as described below.

Impact on operational expenditures

Operational expenditures are directly influenced by project risk and decreasing component commonality, creating additional engineering tasks to modify the module. Operational expenditures and lead time are strongly interdependent. Both dimensions are, to a certain point, substitutable with each other. To reduce lead time, one option would be to allocate additional resources, which increases operational expenditures and vice versa. This substitution has its limits and lead time does not approximate to zero, even with theoretically unlimited resources.

Impact on cost of goods sold and production investment

Decreasing commonality and new internal variants cause additional production investment, since physical modules differ. From a control perspective, investments can be handled as imputed depreciations and be allocated among defined periods. From an engineering perspective, both alternatives do not differ significantly in production costs and thus can be considered approximately equal in cost of goods sold.

Impact on project risk

The electronics module considered in alternative 1 was verified for power tool A. Most general development risks were already assessed and verified. However, since the module will be used in a new system, general uncertainties have to be assessed. In addition, new risks occur in alternative 2, where the module is modified by several engineering disciplines. Following a Failure Modes and Effects Analysis, the additional variance influences system characteristics (e.g. thermal characteristics, mechanical and electrical characteristics). Assuming identical resource allocation, the potential impact, triggered by risks in lead time, is best case 0 %, up to worst case in aggregated risks of 10 %.

Impact on variant-induced costs in manufacturing plant

Assessing the impacts of additional variance in the manufacturing plant, there are savings in increased commonality in cash flow, obsolescence, liquidations, rework, warehousing costs, administration, logistics and flexibility. Negative effects are costs in coordinating and initiating setup. However, the effects analysed were only slightly relevant to the modular concept.

Impact on sales and turnover

At a company level, there is a direct correlation between sales and turnover. Sales in turn are linked to the fulfilment of customer requirements, which was a major discussion during the project: foreseeing the correlation to sales. The provision of a modular system impacts customer requirements. In this case, a customer survey shows that external variance, or customer requirements, was met to a similar or identical level. Assuming the same perceived external variance, identical sales and turnover can be anticipated. However, turnover is also affected by lead times in the project. The later the market introduction takes place the sooner the return on investment will be reached when introducing a new product.

4.6 Internal variance decision and impact model

For the project team, the impact on lead time and therefore on postponed market introduction was decisive in the final choice of alternative. The impact was caused by additional engineering and approval activities and was thus the main reason for the project team to choose alternative 1, voting against increasing internal variance. The impact on customer requirements was assessed, but any resulting positive effects were minor compared to the negative effects of increasing internal variance. The major trade-offs observed were the effects on lead time, operational expenditure, and production invest, compared to slightly better fulfilment of customer requirements. Customer requirements, however, have an effect on turnover. In a final assessment, the return on investment, which in this case was the turnover on expenditures, was the main factor in balancing the overall trade-offs of the two product architecture choices. To visualize the effects in this modularity case, an impact model is set up (Figure 4). The model portrays the interdependencies of effects, providing support for decision makers by providing an overview and transparency in the cause and effect chain of this architecture choice. The impact model in its current state shows the effects of choosing design alternative 2, which decreases modularity, with alternative 1 being the baseline.

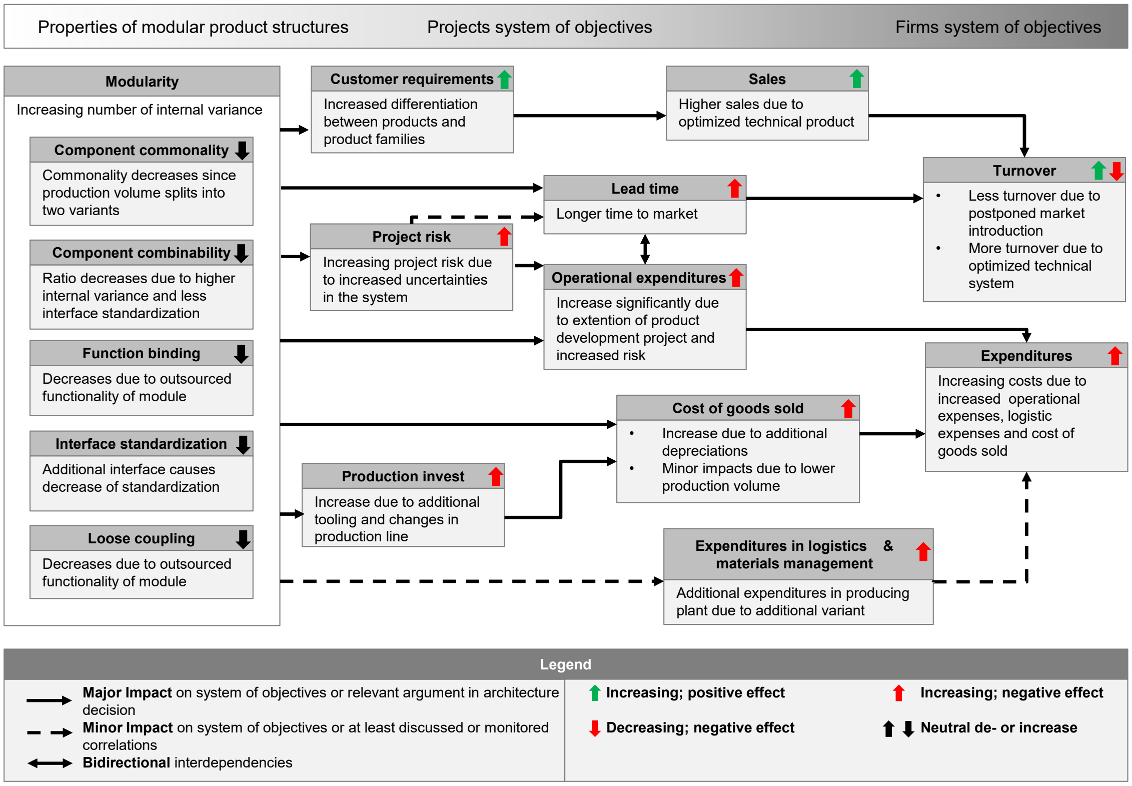

Figure 4. Impact model of increasing internal variance, derived from the case study

The results of this empirical study differ from results in the literature and the study of a power tool family impact model conducted by [Harland and Uddin 2014]. The main difference to this impact model was that the coverage of global markets, coverage of multiple market segments, efficient resource usage, increased quality and reduced procurement costs could not be observed in this case study. However, other relevant effects have been observed that result from the decision makers or project perspective of the impact model demonstrated in this paper. Since the overall goal of this research is to make cause and effect chains of modularity decisions transparent and to support decision makers in this context, the impact model further distinguishes between properties directly influenced by project teams and designers, and systems of objectives to which the project contributes. The impact model not only provides support for the project team within discussions and project meetings, but also enhances the product architecture decision on electronics components within the product family by making the effects of decreasing or increasing modularity transparent. However, the findings and conclusions from this paper have to be validated and extended in future research to prove empirical evidence.

5. Conclusion and future research

To optimize product architecture choices, decision makers have to identify and foresee the impact of their decisions on projects and their company. The case study shows the challenges of identifying influenced objectives, since effects are not always determinable in phases where product architecture definition happens. Two essential challenges for future research were derived in this context, based on current research and the collected data:

Challenge 1: Identifying correlations between modular product structures and systems of objectives

Assessment in single and multiple dimensions is needed for decisions within product development projects. The dimensions are mostly related to time, quality and cost. One conclusion derived from this case study and from literature is that decisions in modular product families have to be based on a set of multiple dimensions. Correlations and interdependencies between factors have to be considered, especially trade-offs and opportunity costs, and the relevant dimensions in the system of objectives comparatively assessed. Recent case studies highlight the need for support, and the challenge in deriving a set of performance indicators for the disciplines involved. To face this challenge, impact models can be used to document and visualize interdependencies and impacts on projects or company objectives; to provide a comparable knowledge database to foster understanding across projects; and to anticipate the effects of modular properties in the long-term.

Challenge 2: Providing support for decision makers

The major challenges in decision making as described in the case study are attributable to the assessment of trade-offs in modularity among several product development projects and balancing trade-offs. Two essential elements for the support we derive from this case study is that trade-offs in quantitative and qualitative attributes of the final products have to be known in detail, and that trade-offs in lead time and resource allocation and therefore in operational expenditures for each of the design stages and each of the components have to be known and made transparent for all stakeholders. Complexity, multiple correlations and lack of transparency in the product portfolio creates a need for a systematic approach to supporting decision makers determining product architecture. This support shall provide sufficient and suitable data and their visualization, and shall especially be capable of pinpointing trade-offs and making conflicts in objectives transparent. Setting up impact models across projects and companies, correlation patterns could be derived and later transformed into dimensions to monitor during product architecture decisions. In addition, this support could be used in existing modularization approaches.

As well as focussing on these identified challenges, this research will be extended to include other product architecture choices and other companies to strengthen empirical evidence [Eisenhardt 1989]. In the long-term, the aim is to provide suitable support for modularization approaches and methodologies that achieve the desired effects of modular approaches, and to enhance support for decision making in product architectures. The goal is to provide a methodology to optimize product portfolios in company systems of objectives by having distinct and precise knowledge of the impacts of modular product structures.

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